Rapid Bursts From GRS 1915+105 with RXTE

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ABSTRACT

The light curves of GRS 1915+105 observed with RXTE on October 15, 1996 reveal a wide range of transient activity including regular bursts with a recurrence time of about 1 minute, irregular bursts, and dips. In contrast to bursts from other sources, a secondary (and a tertiary) weaker burst immediately following the primary burst are observed. Detailed energy spectra indicate that the source softens during the main outburst and successively hardens during the secondary and tertiary bursts. This may imply that the accretion flow has a corona-disk configuration and that the relative contribution of the hot corona decreases during the primary bursts and increases during the secondary and tertiary bursts. The primary burst profile resembles the bursts produced in the time dependent evolutions of accretion disks which are thermally and viscously unstable. The secondary burst may reflect an inward shift of the inner edge of the disk which results in a greater release of gravitational binding energy.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

The hard X-ray transient source, GRS 1915+105, was discovered by Castro-Tirado, Brandt, & Lund (1992) in 1992 using the WATCH all sky monitor instrument onboard the GRANAT satellite. It is located at a distance of about 12.5 ± 1.5 kpc (Mirabel & Rodriguez 1994) with an outburst X-ray luminosity of $\sim 10^{39}$ ergs s^{-1}. In contrast to previous transient sources, GRS 1915+105 is distinguished by the fact that it ejected radio components with apparent superluminal motion up to $v/c = 1.25$ (Mirabel & Rodriguez 1994).

GRS 1915+105 was also observed to be X-ray active in 1994 using the BATSE instrument on CGRO (Harmon et al. 1994; Greiner et al. 1994) and using the SIGMA telescope on GRANAT (Finoguenov et al. 1994). It has been found to be in outburst in 1996 based on observations obtained by the Rossi X-ray Timing Explorer (RXTE). The RXTE observations of GRS 1915+105 have revealed a wide range of transient activity such as the occurrence of dips, irregular bursts (Greiner, Morgan, & Remillard 1996; Belloni et al. 1997; Swank, Chen & Taam 1997), and quasi-periodic oscillations (Chen, Swank, & Taam 1997; Morgan, Remillard, & Greiner 1997). On October 15, 1996, the source entered into an unusual phase of activity in which X-ray bursts were emitted in a quasi regular pattern.

In this Letter we report on the properties of these quasi regular bursts. In §2 the light curves, temporal structure, energy spectra in the burst active and burst inactive state, and spectral fits to these spectra are presented. The interpretation of the bursts in terms of thermal instabilities in the accretion disk and the implications of the spectral fitting are discussed in the final section.

2. OBSERVATIONS

On October 15, 1996 GRS 1915+105 was observed for a total time of about 7.2 hr with the Proportional Counter Array (PCA) onboard RXTE. In these observations, the mean count rate of the source in the 2 - 13 keV energy band was ~ 15000 counts s^{-1}. On this day, the source was situated on the soft branch of the hardness-intensity diagram as described in Chen et al. (1997).

2.1. Burst Profiles

During a period of about 5.5 hours the source emitted a series of quasi regular bursts. The light curve (in the 2-13 keV band) for a portion of this period is illustrated in Figure 1. An important feature is the secondary burst which always follows the primary burst. The occurrence of bursts (both primary and secondary) is quasi regular with recurrence timescales ranging from 60 to 100 s. The transition to the primary burst occurs gradually on the shoulder of the light curve preceding the onset of the main burst. The count rate at peak to that on the shoulder is about a factor of 2 higher, exceeding ~ 20000 counts s^{-1}. Note that the post burst count rate is significantly reduced to about 6000 counts s^{-1}.

The details of the burst profile in the 2 - 13 keV band are shown in Figure 2a with a higher time resolution. The burst exhibits variable oscillations on shorter timescales, which makes the estimate of the burst timescales (rise, decay, duration) difficult. Therefore the variations of the burst timescales with respect to recurrence timescale are not easily quantified. The primary burst is characterized by more structure with variability on a timescale of one second. The main burst has a slow rise (~ 8 s), a fast decline (~ 2 s), and a duration of ~ 10 s. The secondary burst occurs about 3 s later, it is weaker (with a peak count rate $\sim 35\%$ lower than the main burst), has a comparable duration, and

is characterized by a quasi symmetric rise and decay time of ~ 2.5 s. The time between the peaks of the primary and the secondary bursts is about 10 s. In some cases, there is evidence for a much weaker tertiary burst. The peak count rate of the tertiary burst is lower than the secondary burst by about 35% - 50%.

To examine the variations in burst profile with energy, we plot the corresponding light curve in the 13 - 60 keV band in Figure 2b. It is seen that the main burst in the 2-13 keV band is now very weak or does not exist at all. On the other hand, the secondary burst and, especially, the tertiary burst in the 2-13 keV band is very pronounced in the hard energy band. We also note the existence of oscillations (with time scale about 3-10 seconds) which have an amplitude of about 20%, much larger than the corresponding oscillations in the 2-13 keV band. However, the power density spectra of these time series show only broad features and do not reveal any narrow QPO peaks.

The hardness ratio defined as the count rate in the 13-60 keV to 2-13 keV band is illustrated in Figure 2c. It can be seen that the hardness ratio decreases during the main outburst and recovers during the post outburst phase. It reaches a peak (~ 0.09) at the luminosity peak of the tertiary burst. Notice that, the $\sim 3 - 10$ s oscillations are seen in the ratio plot, suggesting a different oscillation strength in these two energy bands.

2.2. Spectra and Energies

Energy spectra have been calculated using recently determined detector response matrices (Version 2.1.2) and background software (version 1.4g of the "pcabackest" tool and versions 1.1, 3.0, and 1.0 of the cosmic ray, the activation, and the X-ray backgrounds respectively). Data from the modes B_2ms_4B_0_35_H were used for 4 channels below 13.1 keV and from the mode E_16us_16B_36_1s for 16 channels above 13.1 keV at the gain of the

epoch of the observation. To investigate the spectral evolution during the bursts, as guided by the ratio plot (computed with 62.5 ms resolution) spectra were determined with 0.625 s resolution on the shoulder prior to the primary burst, at the peaks of the primary burst, the secondary burst, and the tertiary burst. For the shoulder, it was also feasible to use the Standard-2 mode data with 16 s time resolution and 129 energy channels. The energy spectra for the four stages are illustrated in Figure 3a. The spectra are qualitatively similar, but cross at about 15 keV. The ratios of the spectra are sensitive to the differences, as is seen in Figure 3b, where the ratios are calculated with respect to the shoulder spectrum. The spectra are softer during the peaks of the main and second outbursts in comparison to the shoulder of the light curve, whereas the spectrum during the third peak is the hardest.

The best fits to a number of single component spectral models (power law, bremsstrahlung, exponentially cut-off power law, various representations of Comptonization) were much poorer than the combination of a multi-temperature disk black body plus a power law (diskbb + powerlaw in XSPEC, Mitsuda et al. 1984). A 2% systematic error on the model was assumed in the fitting with the most current response matrices because the fits to the Crab spectra imply such errors in the response in the range 3-7 keV and greater than that above 30 keV. With the systematic error the reduced χ^2 for the fits to the spectra summed from 6 bursts with single component models was 4 (versus 70 without the systematic error), while it was 1.5 for the disk black body and power law combination. The binned and event mode data gave results for the shoulder consistent with those for the higher energy resolution Standard-2 data, but with the parameters of the disk component more accurately determined, as expected.

The results are summarized in Table 1. The inferred color temperatures in the inner region of the disk increase from 1.3 keV at the shoulder to 2.4 keV at the peak of the secondary burst, but decrease to ~ 2.2 keV at the tertiary burst peak. The photon indices

are comparable (~ 3.3) at the primary and secondary peaks, but lower (~ 2.9) at the tertiary burst peak. The inferred luminosities of both components vary. In the tertiary peak, a small (inner radius) disk is indicated, but at a relatively low confidence. The parameters are different by $10 - 20\%$ for different versions of the response matrix, but the relative nature of the fits does not change. In comparison to our R_{in} ranging from 32 ± 2 km to 8 ± 3 km, Belloni et al. (1997) obtain a minimum R_{in} of 20.3 ± 0.3 km for data on Oct. 7, 1996 and a maximum of 319 ± 9 km.

Replacing the multi-temperature disk black body with a simple one temperature black body component (bbodyrad in XSPEC) gives nearly as good a fit. The parameters of the power law component are nearly independent of this choice. The black body temperature is about 30% lower than the hottest temperature for the disk, and the inferred radius is about twice that of the disk model. While in principle, effects of scattering and or radiation pressure could be included in models, available models are not consistent or agreed upon. The multicolor black body model is simple, gives good fits to many black hole candidate spectra, and provides a standard of comparison (See discussion by Ebisawa 1994).

3. DISCUSSION

GRS 1915+105 was found to be in a new bursting state during which it emitted quasi regular bursts with a period ranging from 60 - 100 s. The sharp decay and the more gradual recovery of these bursts resemble the burst profiles seen in numerical calculations of thermal/viscous instabilities in accretion disks as reported by Taam & Lin (1984) (see also, Lasota & Pelat 1991; Cannizzo 1996). Within this framework the recovery phase corresponds to the diffusion of matter into the region which has been depleted by the previous outburst. An example of such a calculation is illustrated in Figure 4. Based upon a model consisting of a cool disk and corona and in which the viscosity in the disk

is proportional to the total pressure (see Chen 1995; Abramowicz, Chen & Taam 1995), bursts are produced which resemble those observed, particularly, the broad shoulder and narrow peak features are reproduced. For an accretion rate of $4 \times 10^{-8} M_{\odot} yr^{-1}$ and a black hole mass of $10 M_{\odot}$, the best fit disk parameters are an α viscosity parameter of ~ 0.1 and a dissipation of 85% of the gravitational binding energy in a corona. The bursts in the theoretical light curve are characterized by a recurrence time of about 100 s and a ratio of peak to shoulder and peak to post dip count rates of 2.5 and 5 respectively. The region participating in the outburst involves radii less than about 3×10^8 cm from the central object. We note that, in Belloni et al. (1997) a much smaller viscosity parameter, $\alpha \sim 0.01$, is required to fit the dip time scale.

Theoretical models that we have calculated over a range of a factor of 10 in accretion rate about $4 \times 10^{-8} M_{\odot} yr^{-1}$, in which the corona is absent do not reproduce the observed light curve because the unstable region is too wide leading to larger amplitude outbursts and the lack of a significant shoulder. Hence, the thermal instabilities based upon radiation pressure effects in an optically thick disk (Lightman & Eardley 1974; Shakura & Sunyaev 1976) without a corona are insufficient for detailed fitting to the observational data in a quantitative manner for these accretion rates. Similar burst timescales can be produced for lower mass objects with a corresponding reduction in α. However, the luminosity level is then too low to be consistent with that observed ($> 10^{39}$ erg s^{-1} at a distance of 12.5 kpc).

The detailed spectra of the bursts suggests that the accretion flow can also be interpreted within a picture of a hot corona and a cool disk component. That is, for a fixed fraction of gravitational energy dissipated in the corona (as suggested by the fit to the burst shape), the spectral evolution during the burst reveals that the relative contribution from the cool disk increases during the main outburst and the contribution due to the hot corona increases during the post main outburst state. In addition, as is seen from Table 1,

the power law index is smaller in the shoulder state while the peak black body temperature is higher in the burst state.

A feature of the bursts from GRS 1915+105, which the models do not capture, is the presence of a secondary burst emitted about 10 s after the main burst. We considered whether this burst could be explained as a consequence of radiation feedback on the corona-disk configuration due to the main outburst. In particular, if the radiation emitted from the inner regions cooled the corona in the external region immediately neighboring the inner regions involved in the main outburst, it would destabilize the underlying cool disk (see Ionson & Kuperus 1984). The radial extent of the unstable region would increase as mass in these regions diffuses to the compact object. However, the spectral fitting (see Table 1) does not support this model. Instead, it suggests an inward shift of the inner edge of the disk, which then results in a greater release of gravitational binding energy.

An inward shift of the inner edge of the disk is possible, which would lead to a greater release of gravitational binding energy, provided that the accretion flow was advection dominated before reaching the horizon of the black hole. In other words, the radial extent of the advection dominated flow region is decreased. Chen & Taam (1996) showed that, as the mass accretion rate decreases, the inner edge of the disk shifts inwards. In fact, the third burst can be explained similarly with the difference that the dissipation in the corona increases, which results in a harder spectrum and a smaller power law index. The shift of the inner disk edge would occur at the local diffusion timescale of the innermost region of the disk, which is less than a second for a reasonable viscosity parameter ($\alpha \sim 0.1$).

The occurrence of the quasi regular pattern is not a sole function of the source intensity since during other observations where the mean count rate was also about 15000 counts s^{-1}, the behavior was different, sometimes without significant oscillations (e.g. August 18) and sometimes with larger oscillations but less regular (e.g. June 16). It is possible that

in those cases the source did not remain at the required mass accretion rate level for a sufficiently long time to enter into the rapid burst state.

The smallest radius for the inner edge (ie., the location of the sonic point) of the disk lies between the marginally bound and the last stable orbits of a test particle, which is $6M/M_{\odot} < R_{in}^{\min}(\mathrm{km}) < 9M/M_{\odot}$ for a non-rotating Schwarzschild, and $R_{in}^{\min}(\mathrm{km}) \gtrsim 1.5M/M_{\odot}$ for a maximumally rotating Kerr black hole of mass M. If one interpretates the 67 Hz QPO in terms of the disk oscillation models (Chen & Taam 1995; Morgan & Remillard 1996; Milsom & Taam 1996; Morgan, Remillard, & Greiner 1997; Nowak, Wagoner, Begelman, & Lehr 1997), then the black hole mass implied is either $10M_{\odot}$ (Schwarzschild) or $33M_{\odot}$ (Kerr), which thus gives a minimum radius of $\sim 50-60$ km independent on the rotation of the black hole. The disk radii obtained in the spectral fits are underestimates since effects due to scattering in the disk atmosphere would imply an effective temperature which may be smaller by a factor of 1.7 (Shimura & Takahara 1995). This "hardening factor" would lead to an increase in the radius by a factor of 3, that is, $R_{in} \sim 24-39$ km. In addition, if the effective emission area of the disk is less than the surface area of the disk, in the case where the disk is patchy or has ring-like structures, the radius can be even larger (e.g., Haardt, Maraschi, & Ghisellini 1994). Thus, we conclude that the inner radius deduced from the spectral fitting is likely to be a lower limit, and is consistent with GRS 1915+105 being either a non-rotating ($\sim 10M_{\odot}$) or a rotating ($\sim 30M_{\odot}$) black hole.

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Fig. 1.— Light curve of GRS 1915+105 on 15 October 1996 revealing periodic outburst behavior. The data corresponds to the 2-13 keV count rate in the 5 XTE/PCA detectors. Note that the main outburst is followed by a smaller secondary outburst.

Fig. 2.— (a) Upper panel, expanded view of one of the bursts in Figure 1. The horizontal scale of the light curve is enlarged to reveal the detailed burst profile. (b) Middle panel, the corresponding light curve in the energy band of 13 - 32 keV. (c) Lower panel, the hardness ratio corresponding to the ratio of the count rate at 13 - 32 keV to that at 2 - 13 keV.

Fig. 3.— (a) Left panel, energy spectra during the four stages of a burst. The square, triangle, asterik, and circle are for the spectra on the primary peak, the second peak, the tertiary peak, and the shoulder respectively. (b) Right panel, spectrum ratio with respect to the shoulder. The square, triangle, and asterik are for the the primary peak, the second peak and the tertiary peak respectively.

Fig. 4.— The theoretical light curve of the disk corona system based upon a model disk extending to 10^9 cm from a black hole. Note the presence of a shoulder before the burst and the post burst dip.

Location	T_{in}(keV)	R_{in}(km)	Γ	K	L_{disk}	$\dot{M}_{disk}$	L_{PL}
Shoulder	1.35 ± 0.04	30 ± 2	3.02 ± 0.03	60 ± 5	0.40	0.93	$1.7E^{-1.04}$
Peak 1	1.73 ± 0.03	32 ± 2	3.30 ± 0.08	93 ± 23	1.22	3.1	$2.1E^{-1.30}$
Peak 2	2.44 ± 0.04	13 ± 1	3.24 ± 0.07	63 ± 13	0.81	0.84	$1.5E^{-1.24}$
Peak 3	2.20 ± 0.15	8 ± 2	2.88 ± 0.06	34.5 ± 6	0.19	0.12	$1.2E^{-0.88}$

Table 1: Best fit parameters: The column absorption N_H in $10^{22}\,cm^{-2}$ (assumed to be the same at the four stages of the burst), was 6.3±1.0 with version 2.1.2 of the response matrices. T_{in} and R_{in} are obtained from the disk-blackbody spectrum, they represent respectively the temperature and the radius at the inner edge of the disk. Γ (dimensionless) and K (in photons/keV/cm^2/s) are the photon index and the coefficient of the power law. The bolometric disk-blackbody luminosity , $L_{disk} = 4\pi R_{in}^2 \sigma T_{in}^4$, and the power law component luminosity of energy above E, L_{PL}, are in the unit of $10^{39}\,ergs\,s^{-1}$, and E is in unit of keV. We have assumed that the distance to the source is $d = 12.5$ kpc and the inclination angle is $i = 70$ degrees (Mirabel & Rodrigues 1994). $\dot{M} = 8\pi R_{in}^3 \sigma T_{in}^4 / 3GM$ is given in units of $10^{-8} M_{\odot} yr^{-1}$ for the optically thick disk alone, for a compact object mass of $10 M_{\odot}$.